The Role of Physical Experiments in Advancing the Design of Aircraft Gas Turbine Compressors

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Tony Strazisar
NASA-Glenn Research Center

Comments on Experiments vs Tests

The Changing Roles between Analysis and Experiment

Examples of Impact from Experiments:

- **Rotor blade geometry variations**
- **Rotor blade surface finish**
- **Rotor hub leakage**
- **Stator hub loss**
- **Rotor tip flow and stability**

Experiments vs Tests

Experiment

- Designed to explore a particular problem or hypotheses
- Often performed in simplified geometry (low speed, single stage, isolated blade row, etc)
- Often conducted at university, government, industrial research labs
- Difficult to do in a product development environment

Test

- Designed to explore/document performance, validate design
- Performed on complex components (multistage, high speed)
- Conducted in industrial environment
- Essential component in a product development environment

Impact of Experiments on Compressor Design

Path 1:

Experimental data → improved CFD/analysis → improved design methods

Path 2:

Experimental data → improved understanding → improved design/ fab methods

Analysis vs Experiment

Which is the Horse and which is the Cart?

The 1980's

Emerging CFD
- **2D → 3D**
- **Inviscid → Viscous**
- **Steady → Unsteady**

Emerging measurement methods
- **Holography**
- **LDV**

The ability to *calculate* within blade rows created a *drive* that fueled advancement of methods that could *measure* within blade rows

Analysis vs Experiment

Which is the Horse and which is the Cart?

The 1990's

LDV data sets DLR, NASA
- **Rotors (steady)**
- **Stages (unsteady)**

Refined CFD methods
- **Turbulence models**
- **Grids & numerics**
- **Leakage models**

The existence of high-quality, non-intrusive *data sets* enabled a drive for continued refinement of *CFD methods* and best practices

Use of NASA LDV data for CFD development & assessment

	1984 NASA Fan Rotor 67	1994 NASA Core Compressor Rotor 37
Data Requests	28	32 during ASME exercise 100^{+} by 2003
Known Publications	14	28 (1998)
Organized CFD Validation Efforts	—	ASME 12 participants AGARD WG26 11 ERCOFTAC 5 (as of 1997) APACETT 7

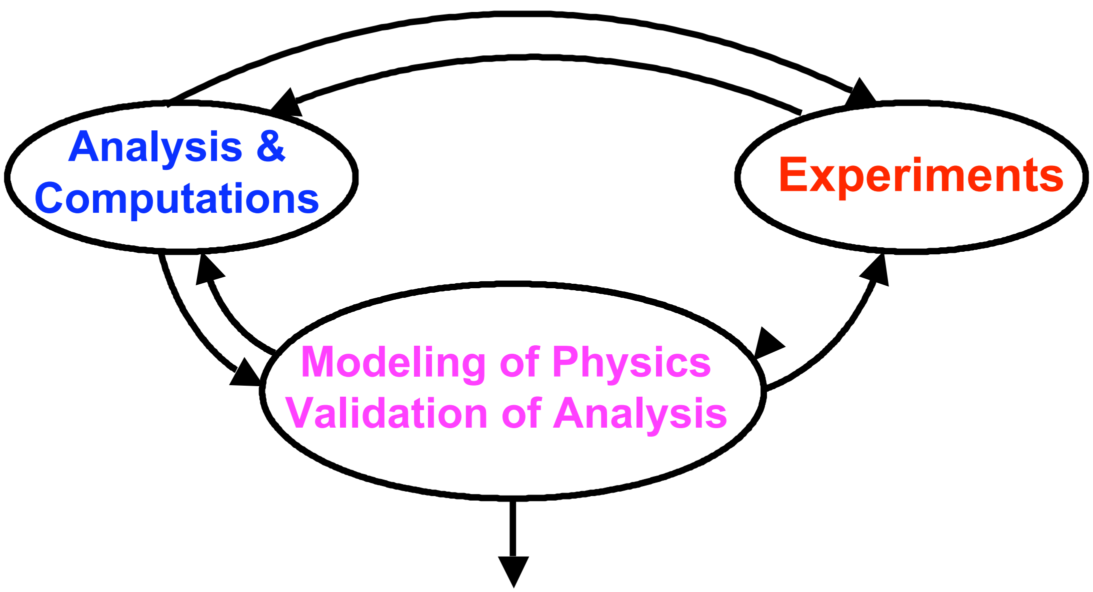
1994	1996	1997
Nothing works!	*There is hope!*	*Is there hope?*

Charles Hirsch, ERCOFTAC comments

Analysis vs Experiment

Which is the Horse and which is the Cart?

Horse + Cart = Team !



Understanding of Fluid & Thermal Physics
Accurate Predictive Capability

Rotor Blade Geometry Variations

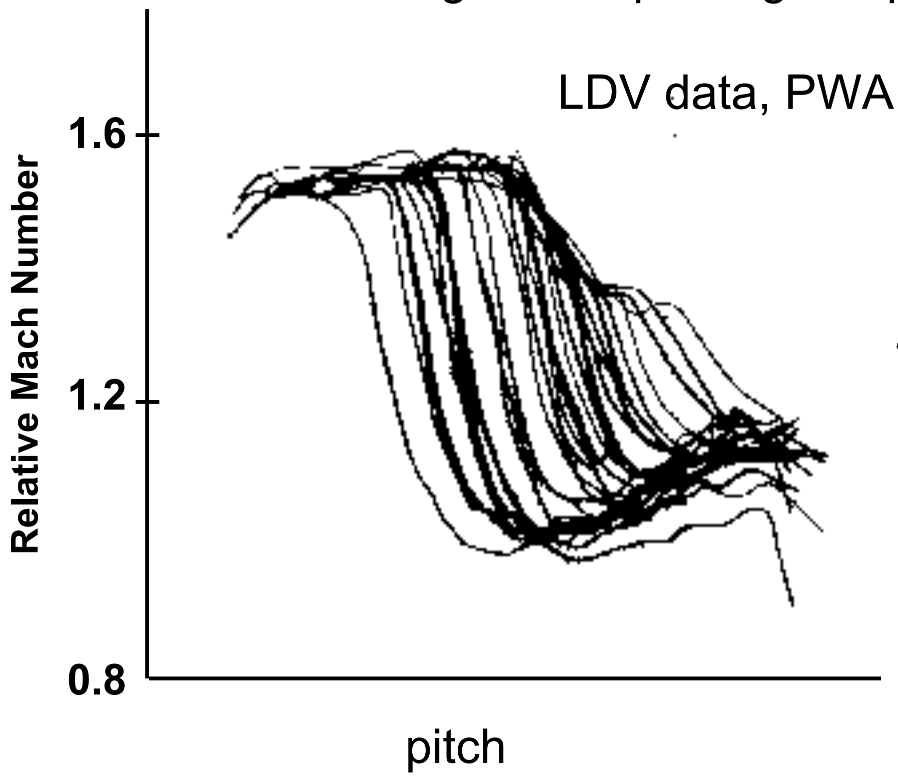
Myths:

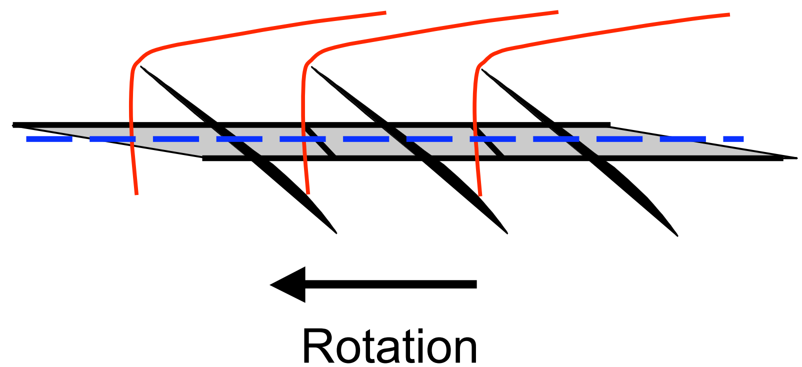
- **All blade passages in a rotor have the same geometry**
- **Strain gauges are minimally intrusive**

Rotor Blade Geometry Variations

Part-span damper manufacturing tolerance leads to significant passage-to-passage shock variations

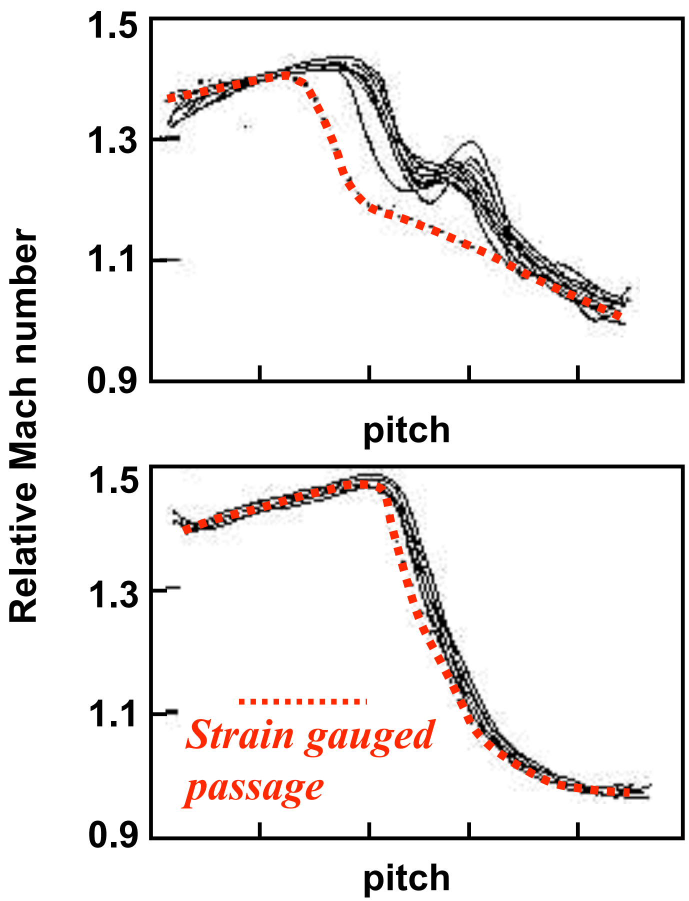
LDV data, PWA 1800 ft/sec fan

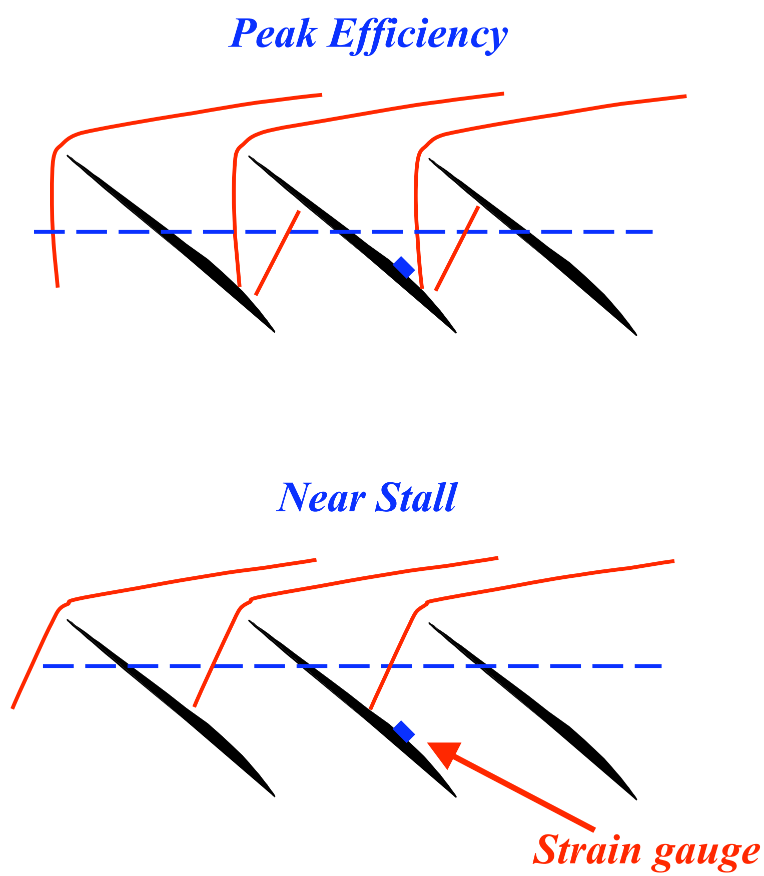




Rotor Blade Geometry Variations

Impact of strain gauge installation,
NASA fan rotor 67





Rotor Blade Surface Finish

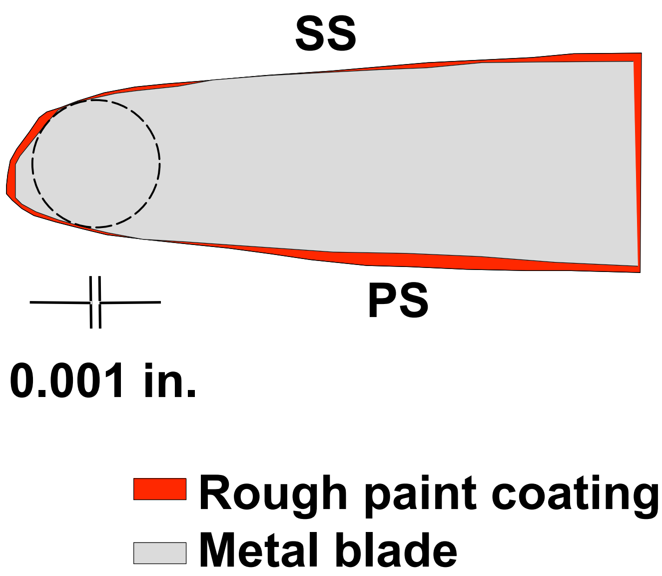
an unplanned experiment

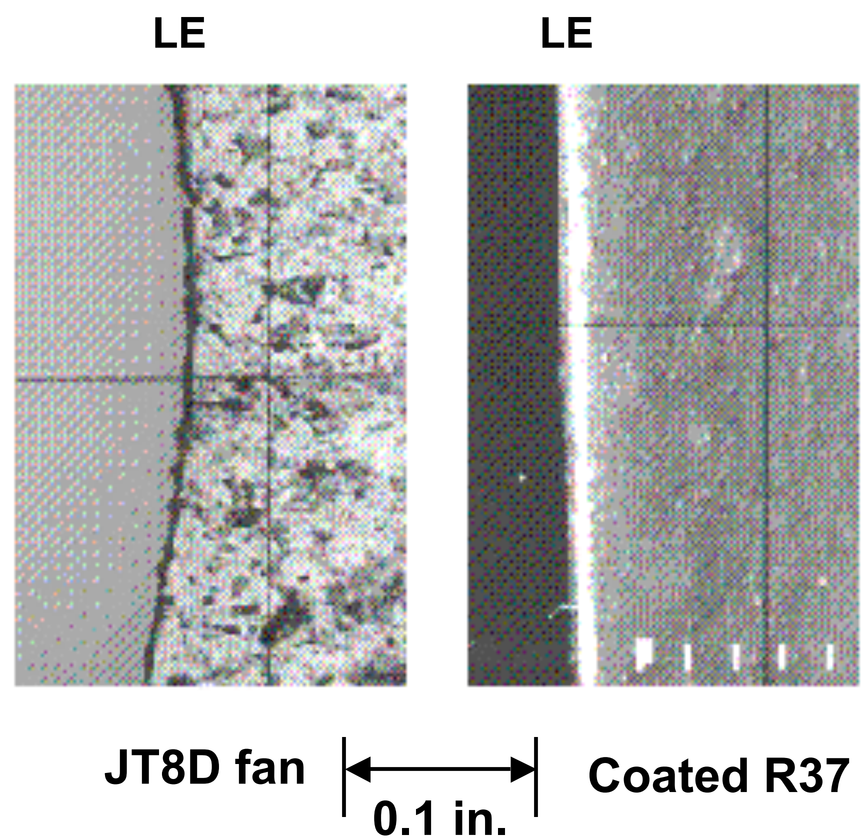
A lesson in the importance of leading edges

A take-away message for fabrication techniques

Rotor Blade Surface Finish

NASA Rotor 37, U_{tip} = 1492 ft/sec





Rotor Blade Surface Finish

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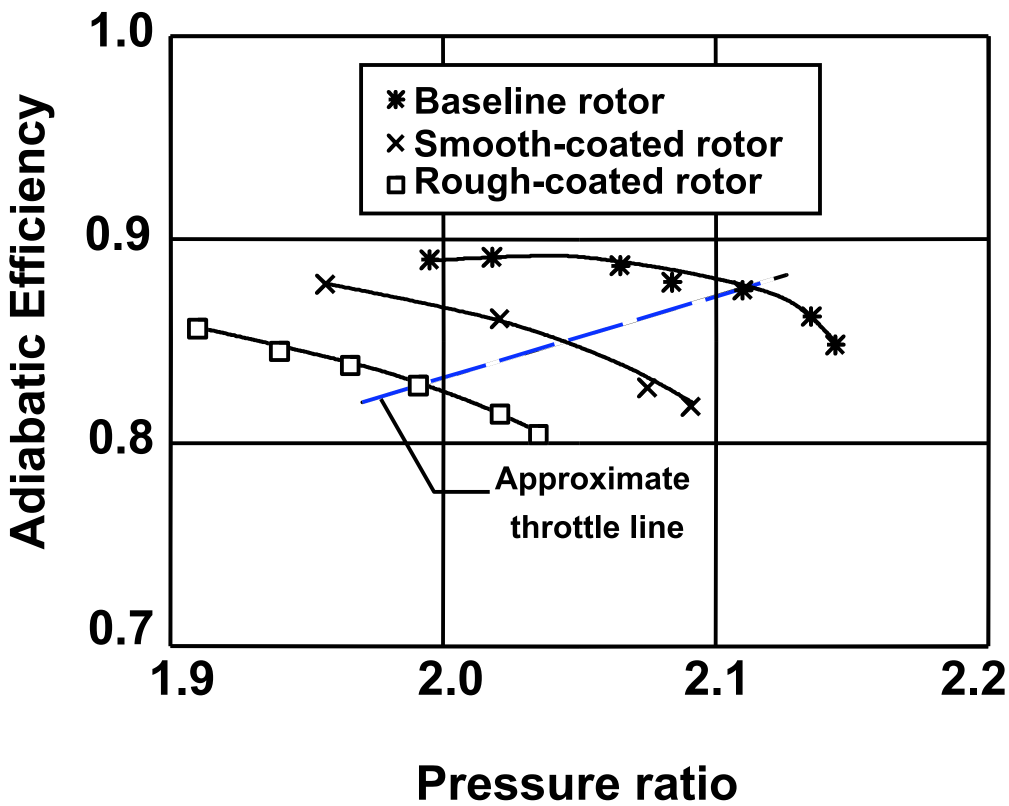

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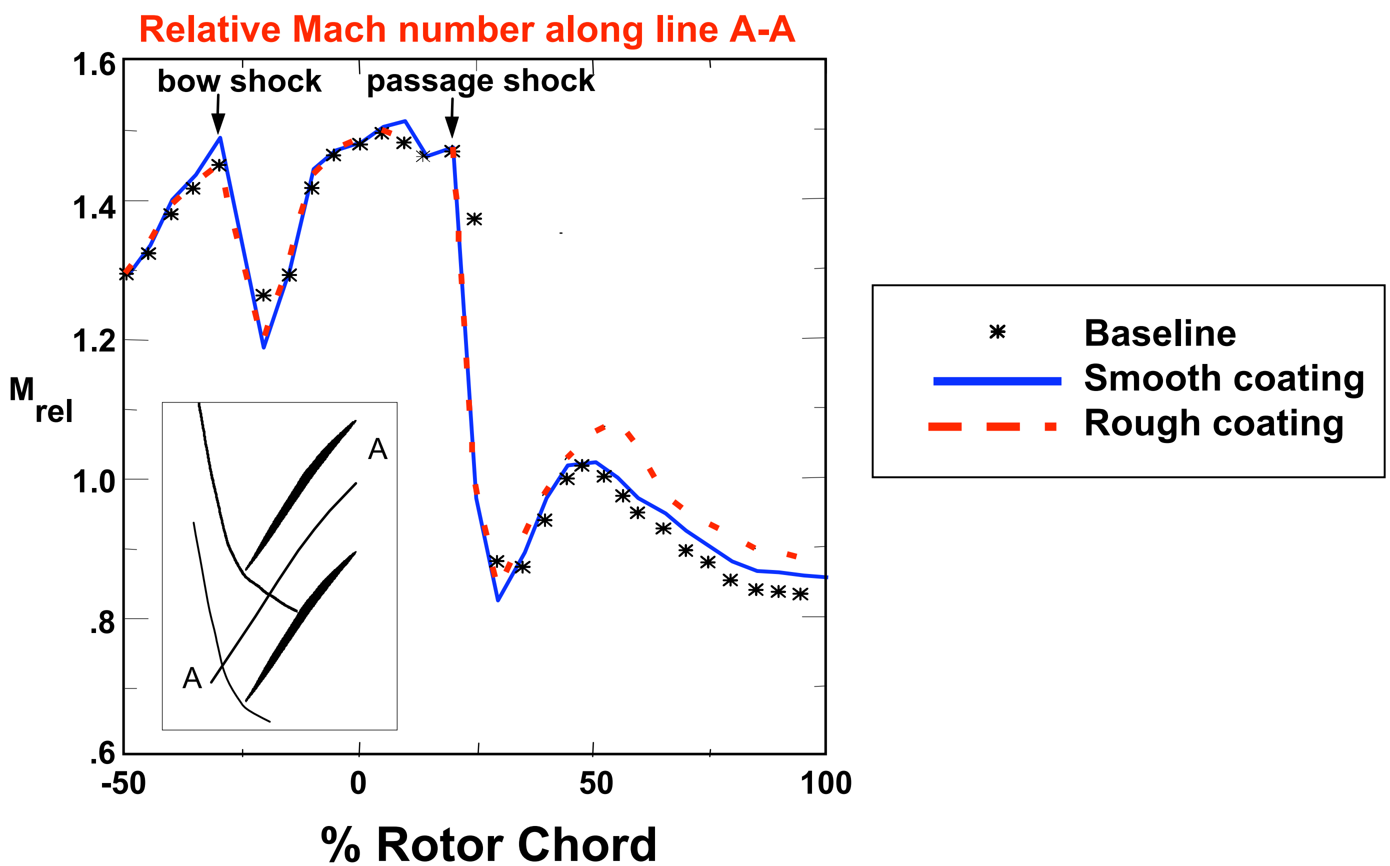

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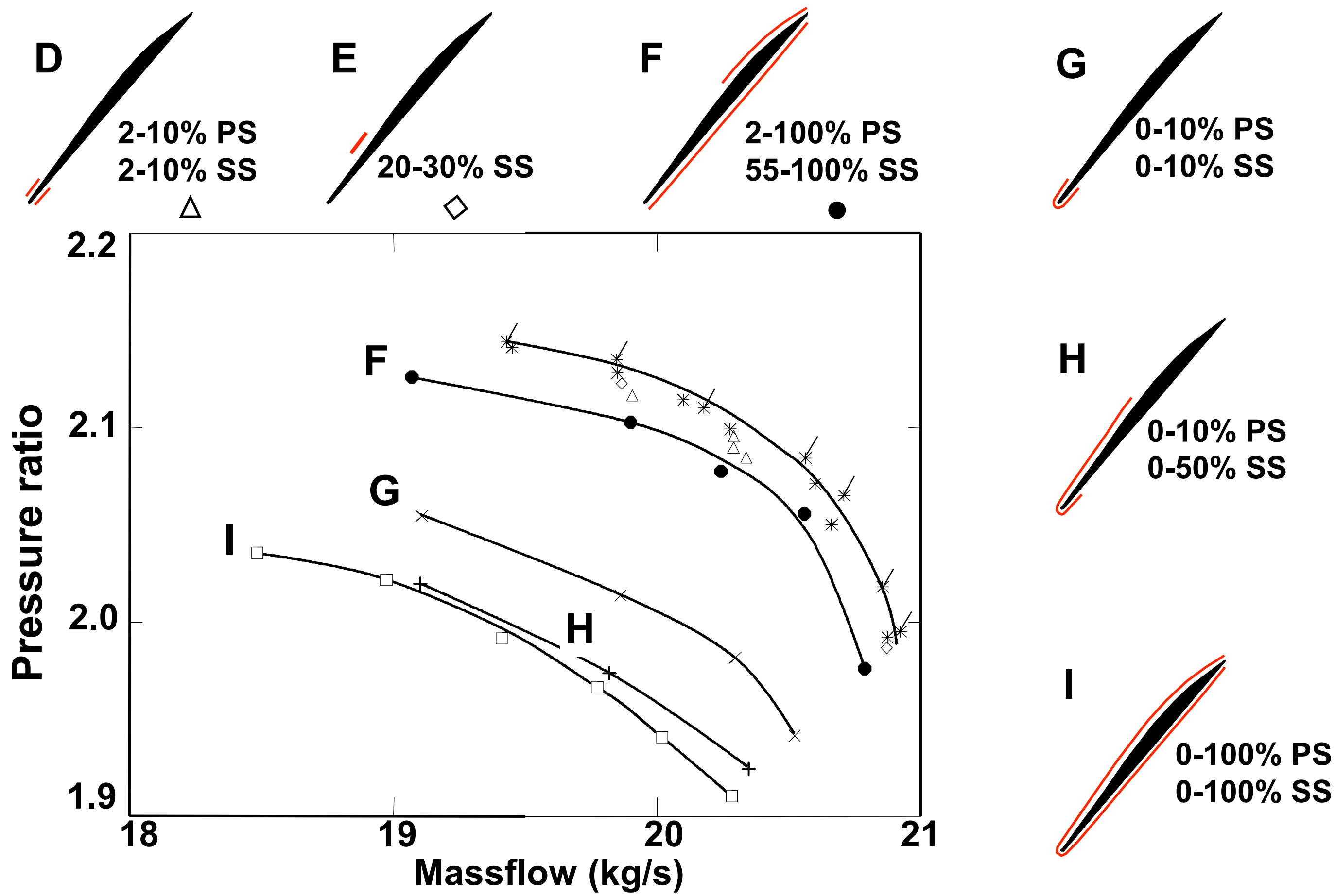

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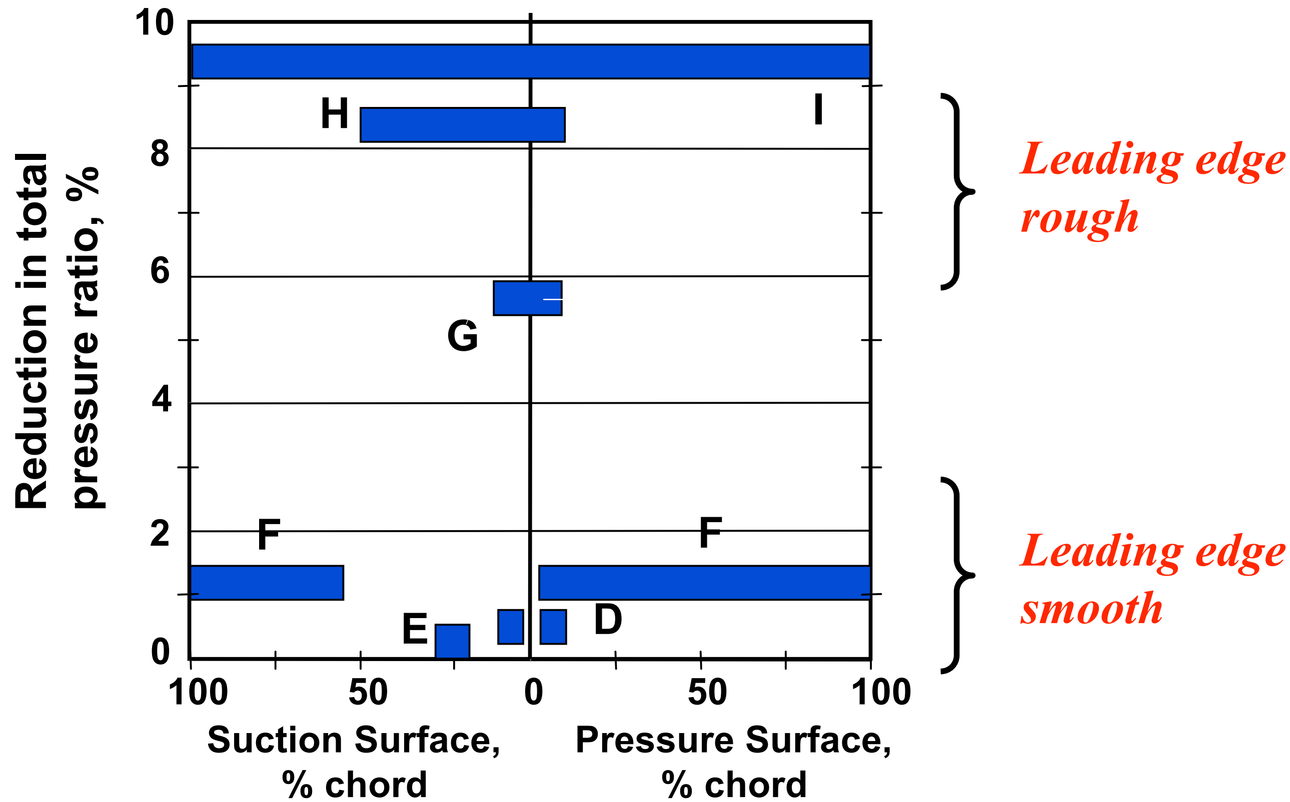


Rotor Hub Leakage

an experiment driven by CFD assessment

The devil is in the details…

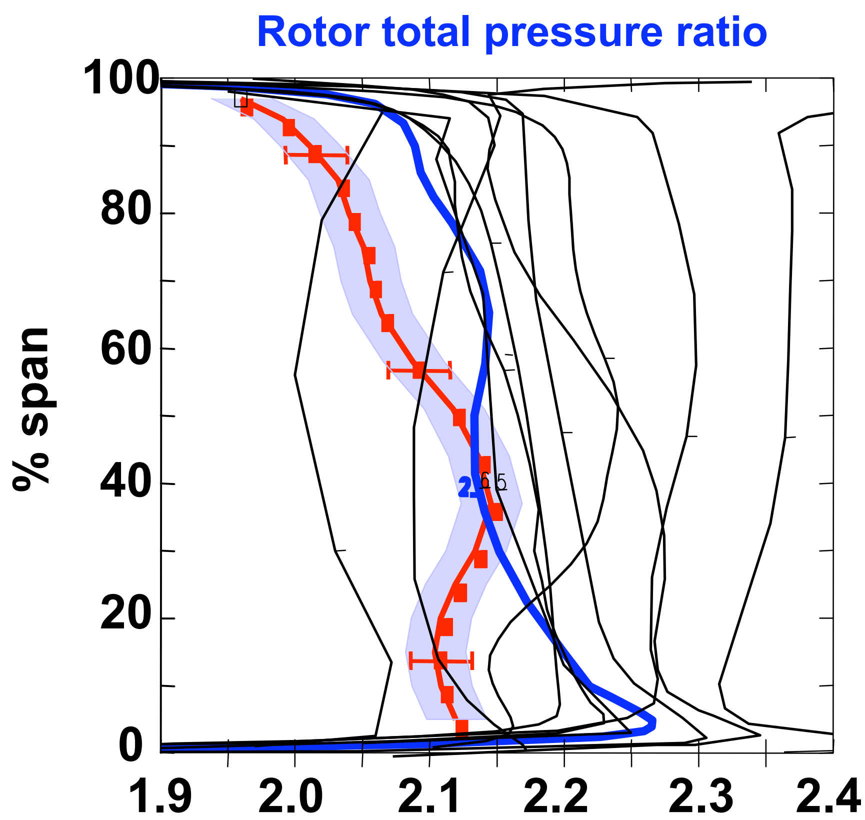
A lesson in the power of leakage flows

A take-away message for rotor seals

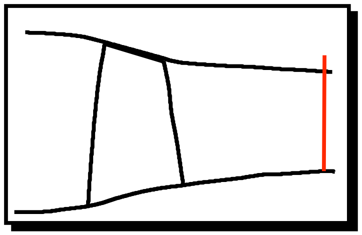
An example of flow feature modeling

Rotor Hub Leakage

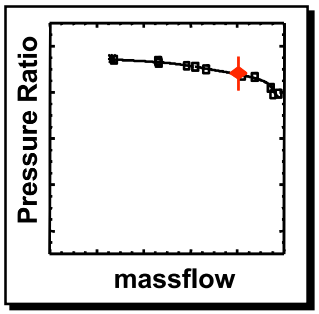
NASA Rotor 37, U_{tip} = 1492 ft/sec



Measurement plane

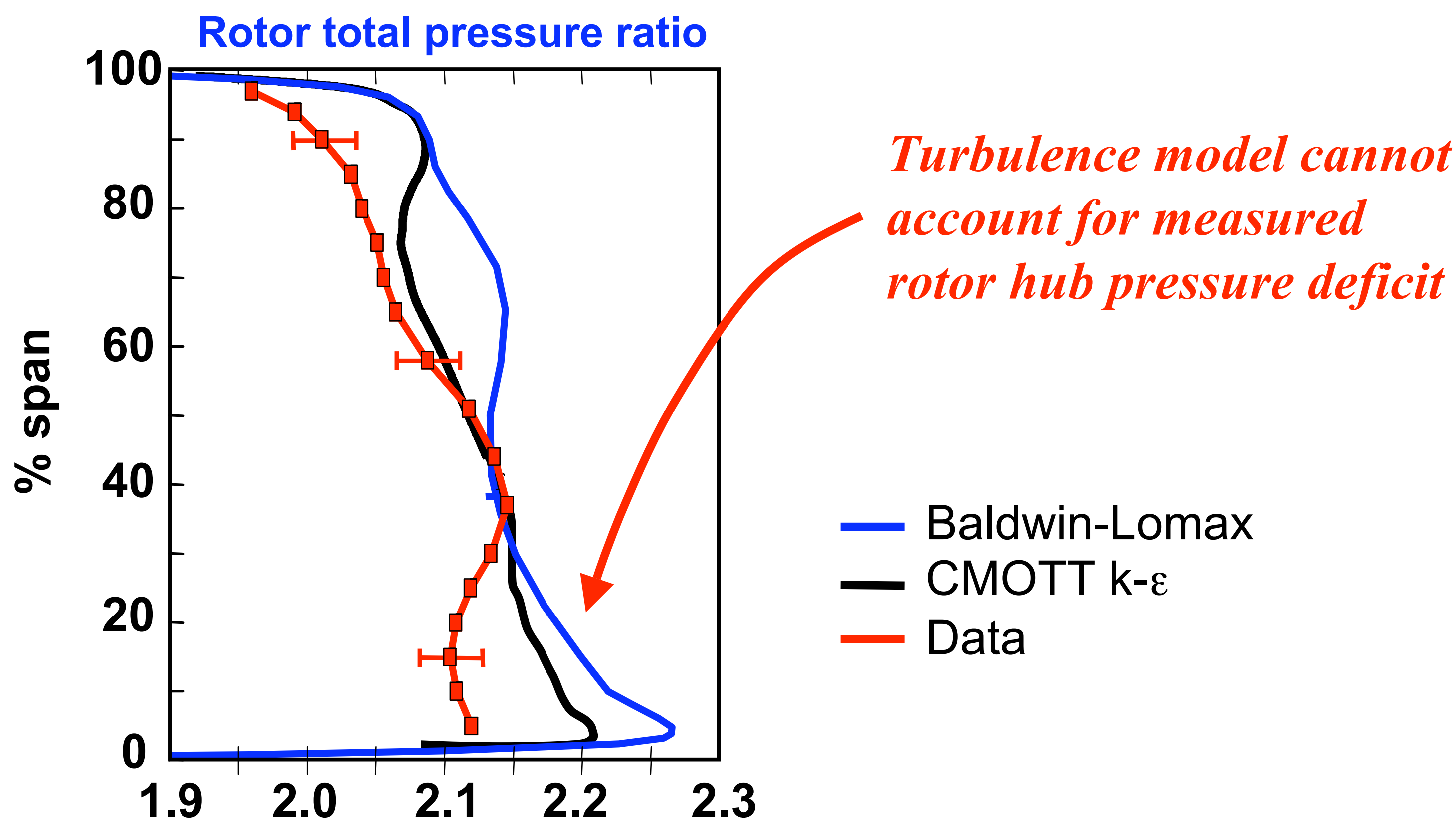


Operating point



Rotor Hub Leakage

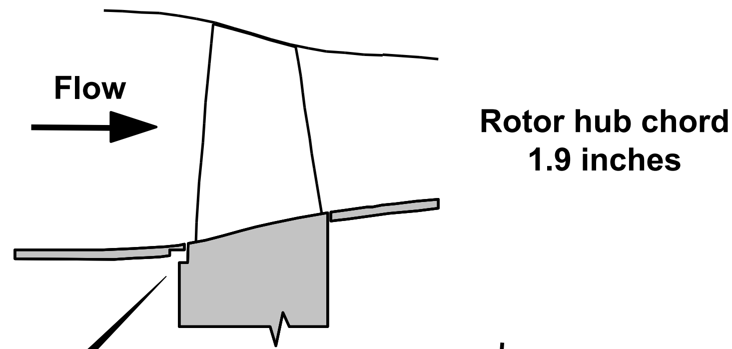
NASA Rotor 37, U_{tip} = 1492 ft/sec

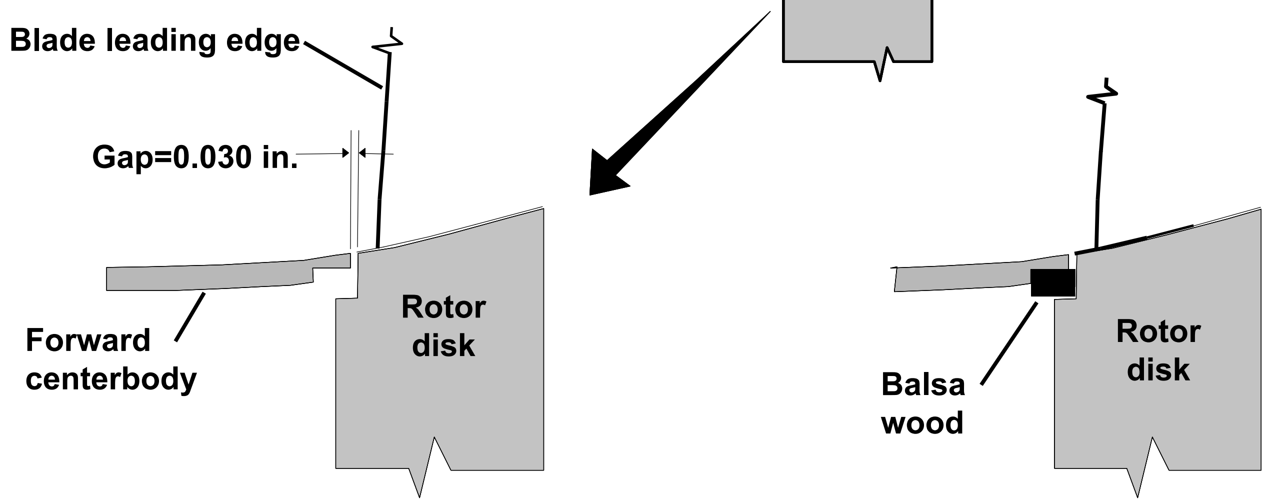


Rotor Hub Leakage

NASA Rotors 35 & 37, U_{tip} = 1492 ft/sec

But…
The test rig contained a <u>blind</u> upstream cavity

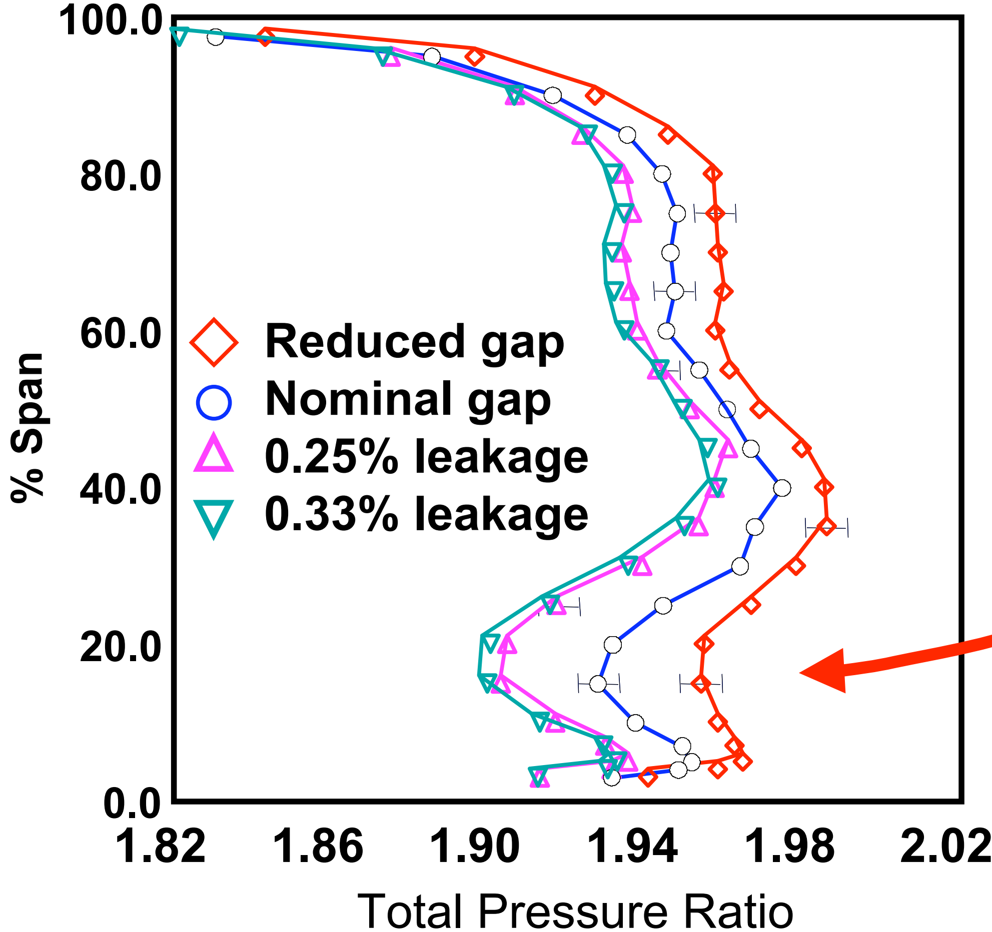




Nominal Gap ***Reduced Gap***

Rotor Hub Leakage

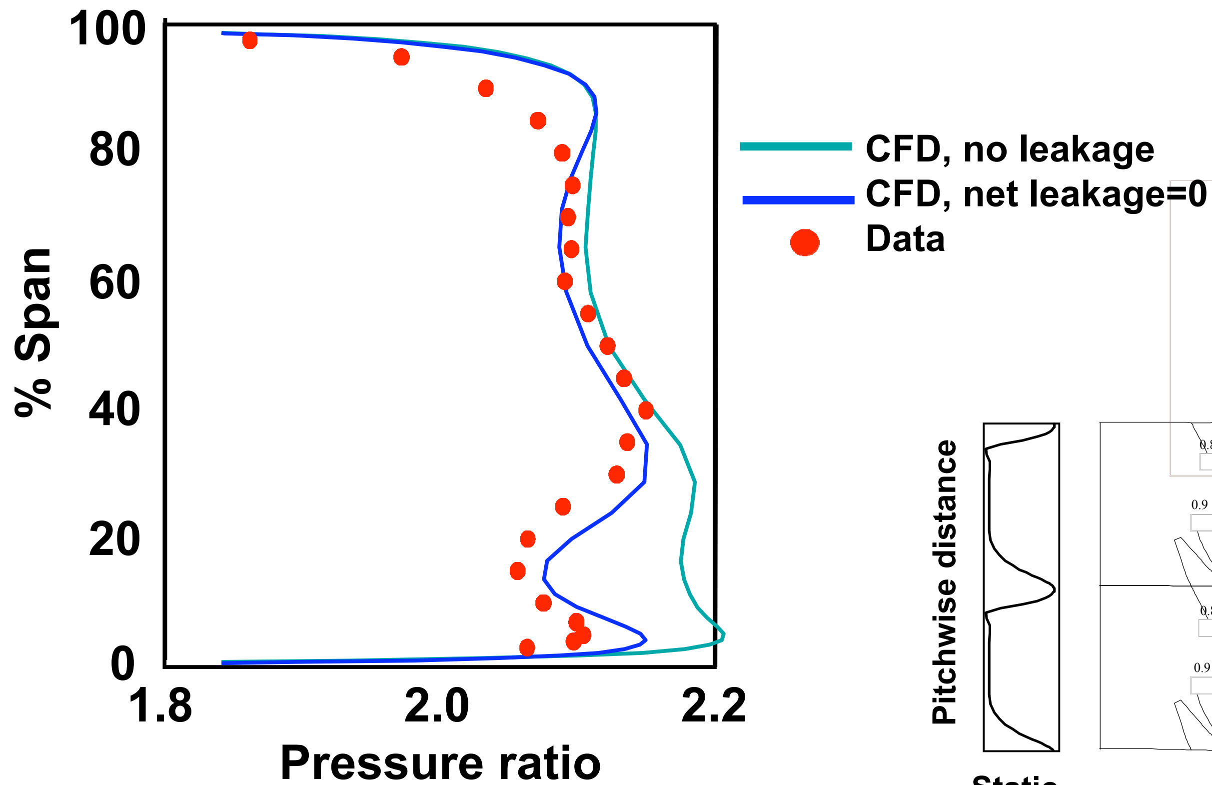
NASA Rotor 35, U_{tip} = 1492 ft/sec

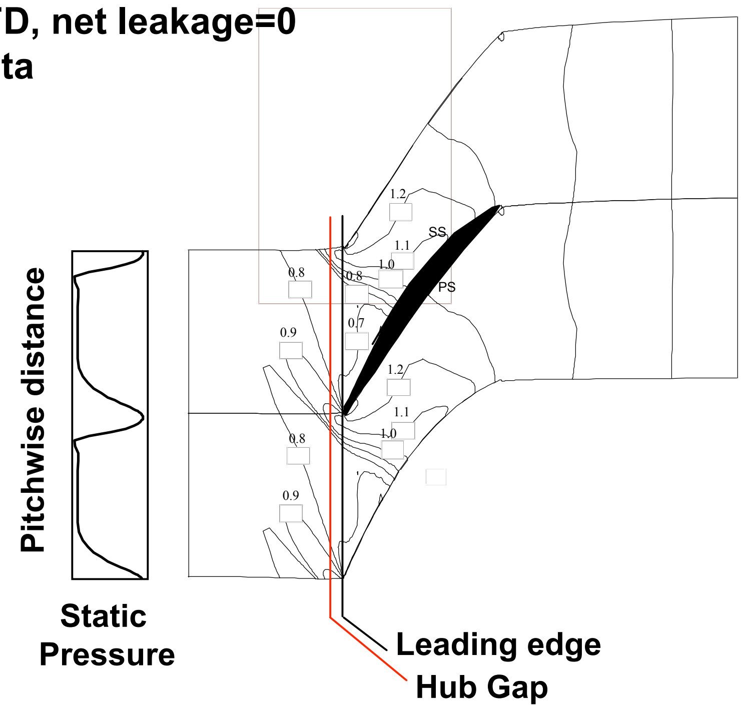


Experimental data confirms sensitivity to hub leakage

Rotor Hub Leakage

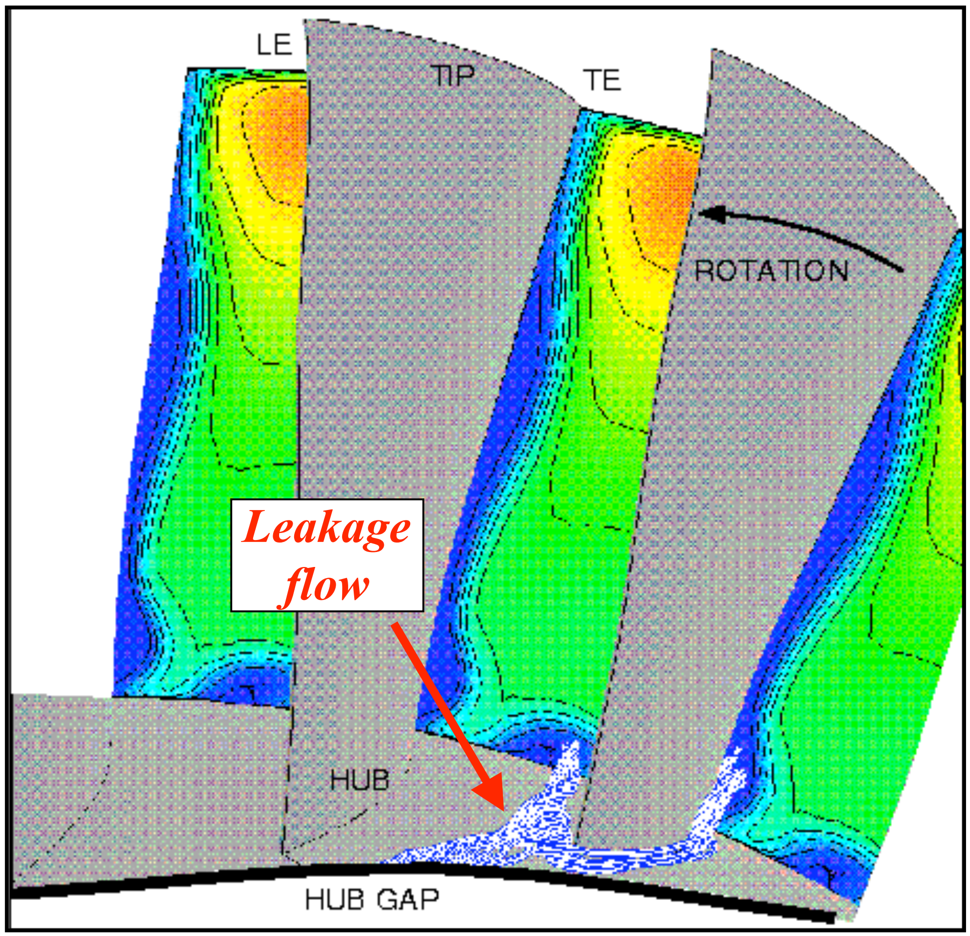
NASA Rotor 37, U_{tip} = 1492 ft/sec



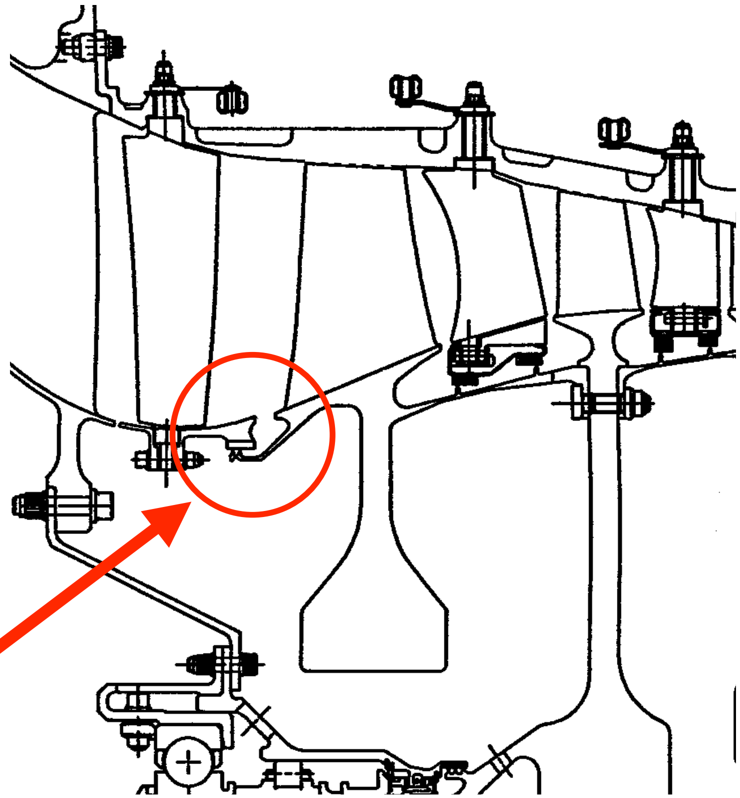


Rotor Hub Leakage

NASA Rotor 37, U_{tip} = 1492 ft/sec



Rotor Hub Leakage



"Discourager" seal

Stator Hub Loss

a parametric study

The devil is in the details…

A lesson in the power of leakage flows

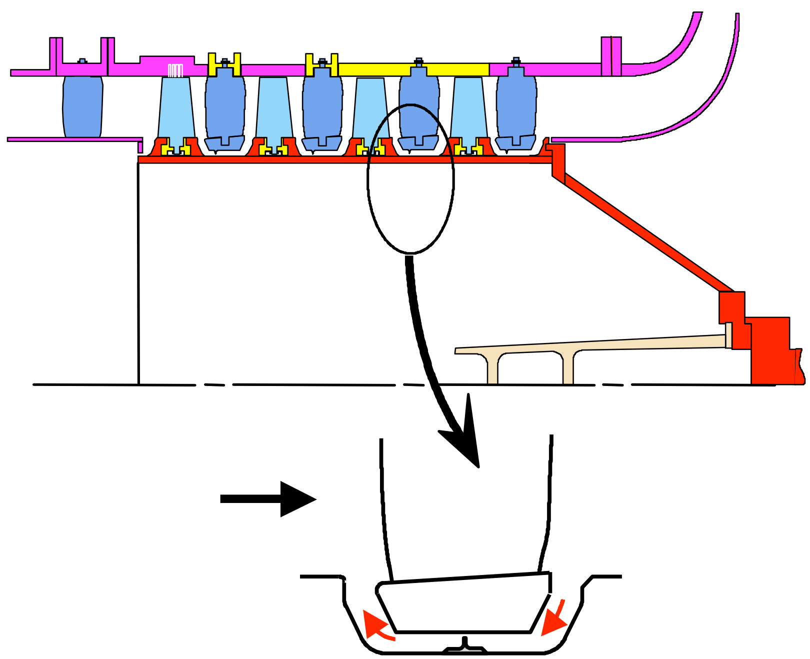
A take-away message for stator labyrinth seals

An example of flow feature modeling

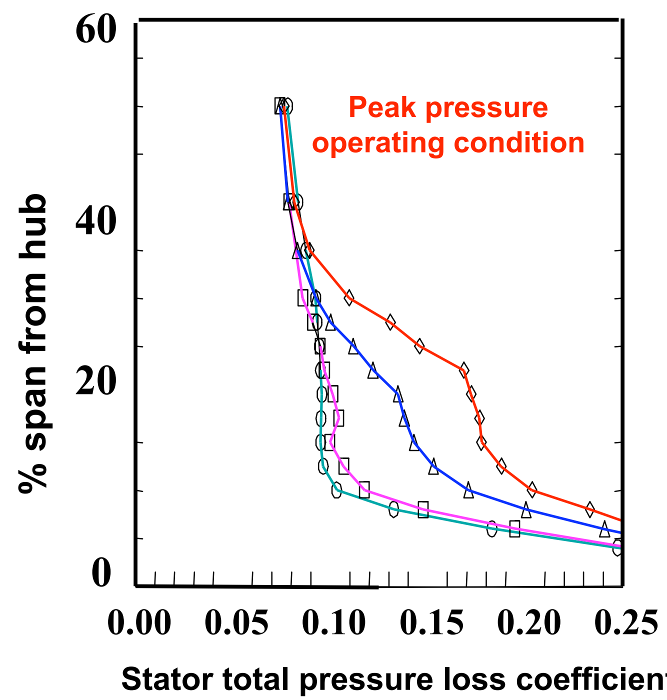
Stator Hub Loss

Sensitivity of loss to clearance is comparable to that for rotor tip clearance

NASA-Glenn Low Speed Axial Compressor



Stator shroud leakage flow



○ "No leakage" 0.2%
□ Baseline leakage 0.5%
△ Increased leakage 0.9%
◇ Maximum leakage 1.3%

Rotor Tip Flow & Stability

experiments lead the way

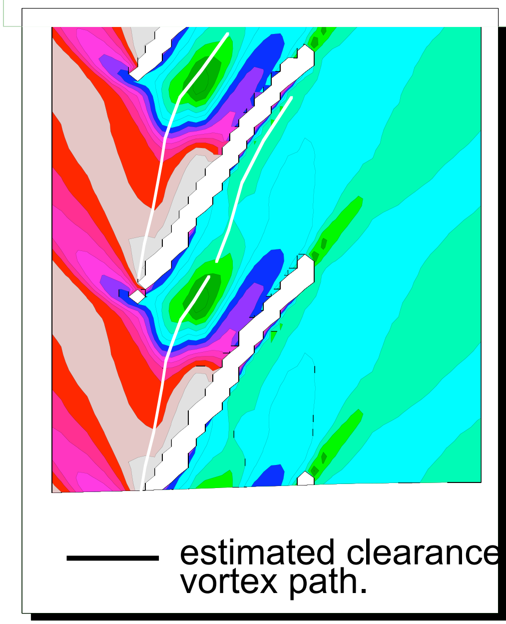
Understanding a detrimental flow feature does not necessarily mean it can be eliminated by design

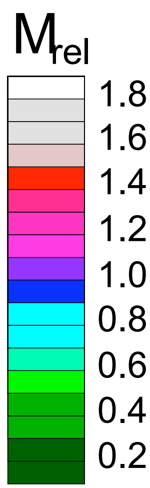
Understanding a detrimental flow feature can lead to an engineering solution

Rotor Tip Clearance Flow & Stability

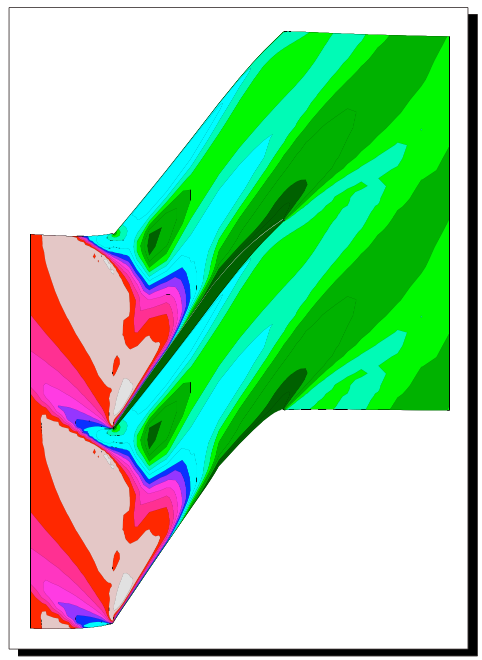
The rotor tip clearance vortex causes large total pressure loss and blockage in the tip region, limiting the stable operating range of the rotor.

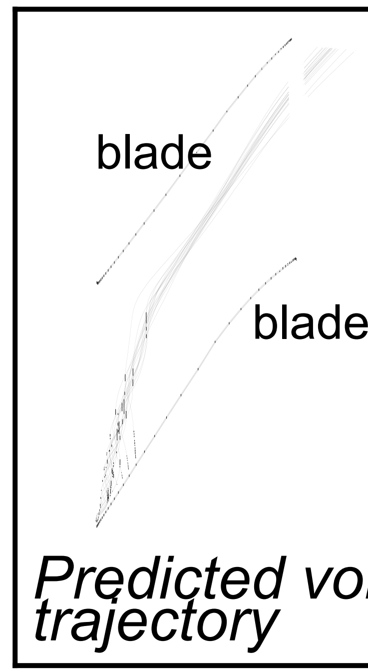
Laser Anemometer Measurements, 95% span





3D Navier-Stokes Analysis



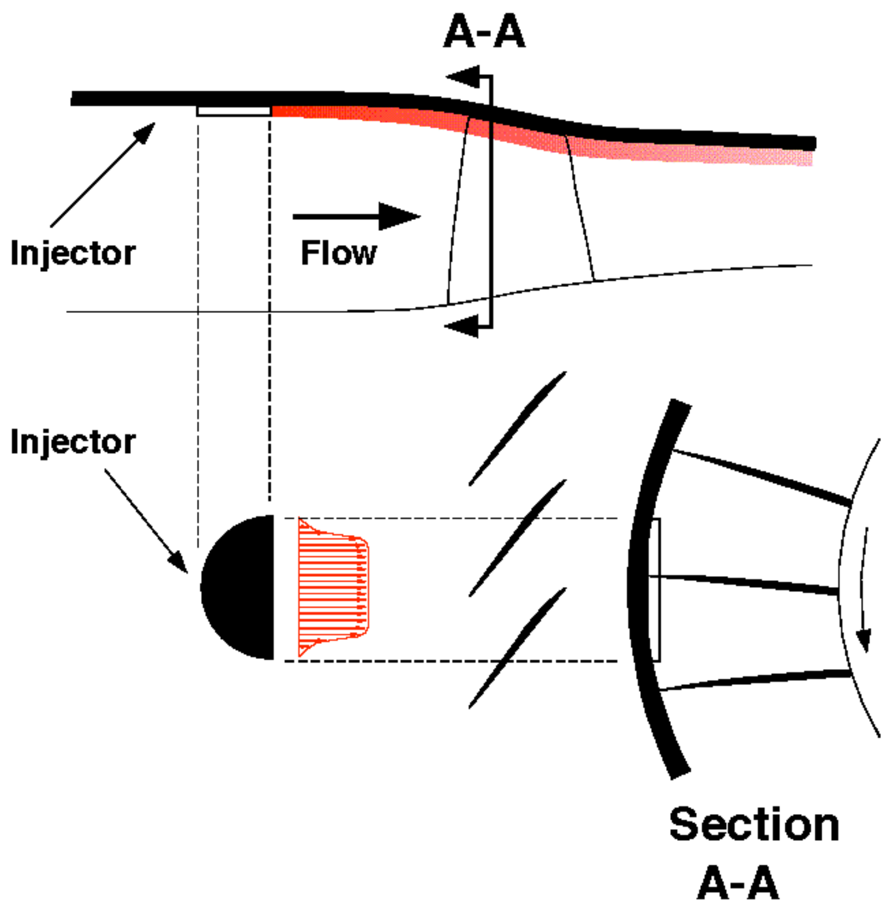


Rotor Tip Clearance Flow & Stability

Solution	Pro	Con
Reduce rotor tip loading	Increased operating range	Reduced pressure ratio
Casing treatment	Increased range	· Reduced efficiency throughout the mission · Difficult to "turn off" · Increased temperature at the tip
Discrete tip injection	· Increased range · Can be "turned off" · No temperature increase at the tip	· Additional plumbing · Rotor excitation · Reduced eff when used

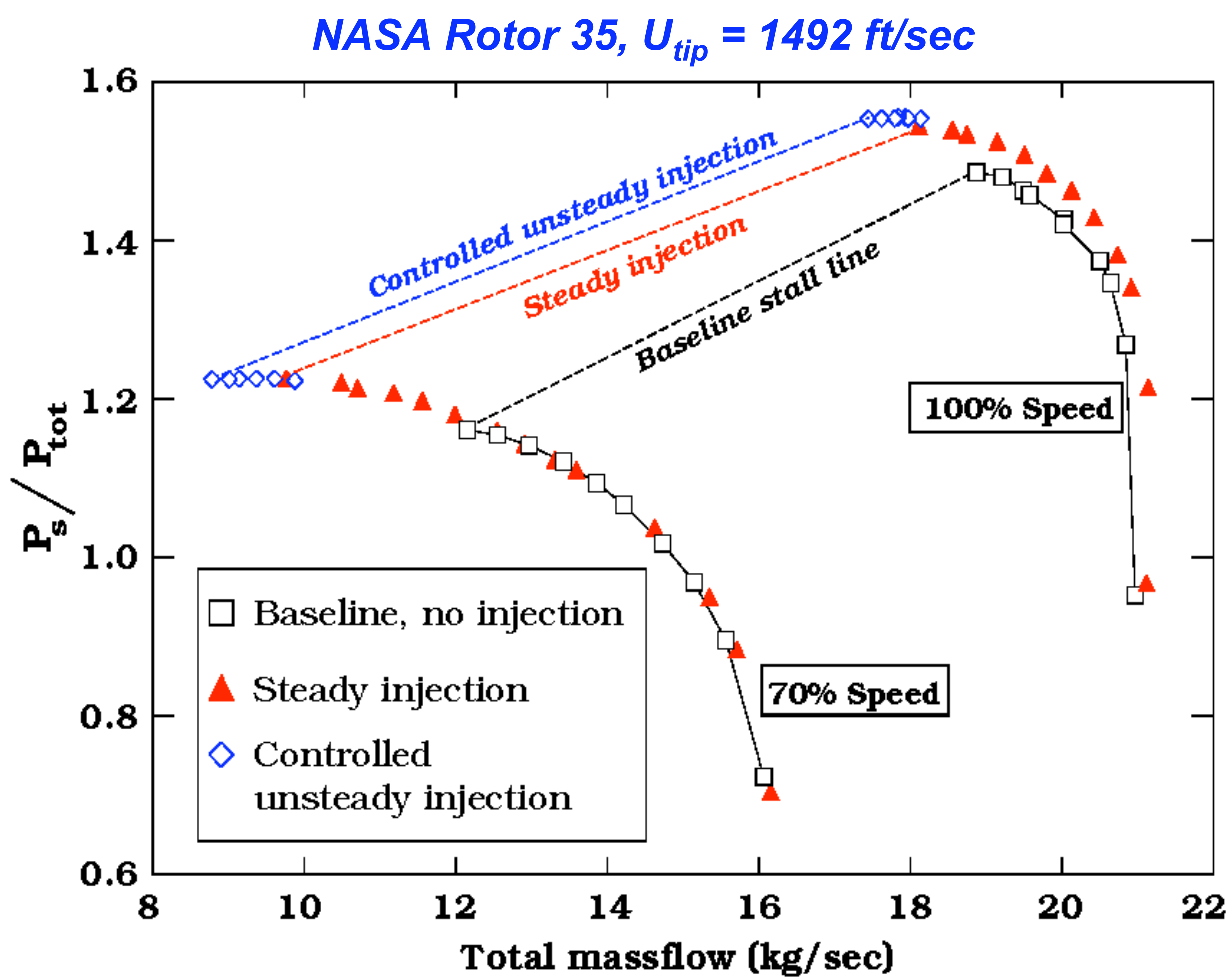
Rotor Tip Clearance Flow & Stability

3-12 injectors around circumference



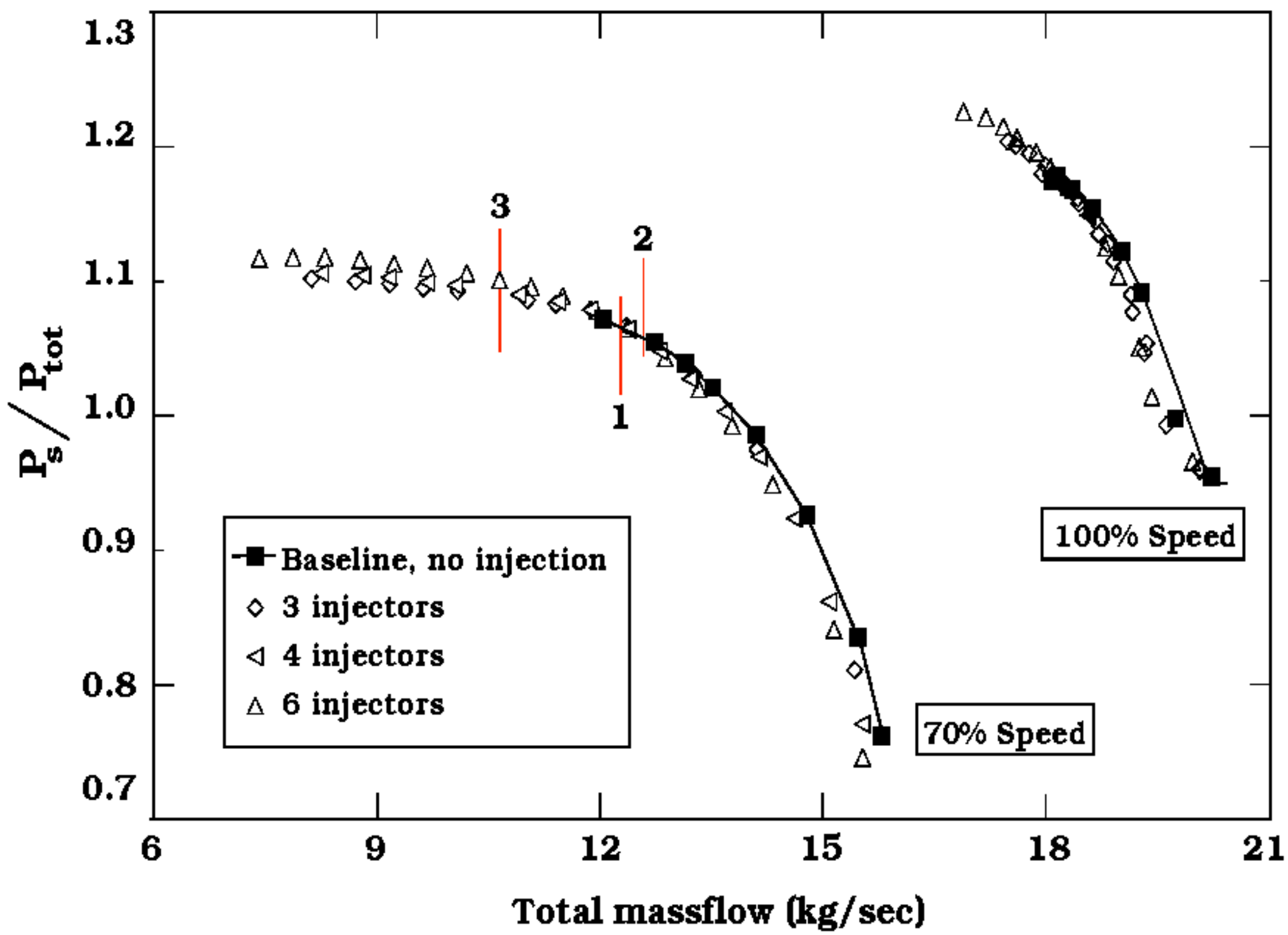
The Role of Experiments in Advancing the Design of Gas Turbine Compressors

Rotor Tip Clearance Flow & Stability



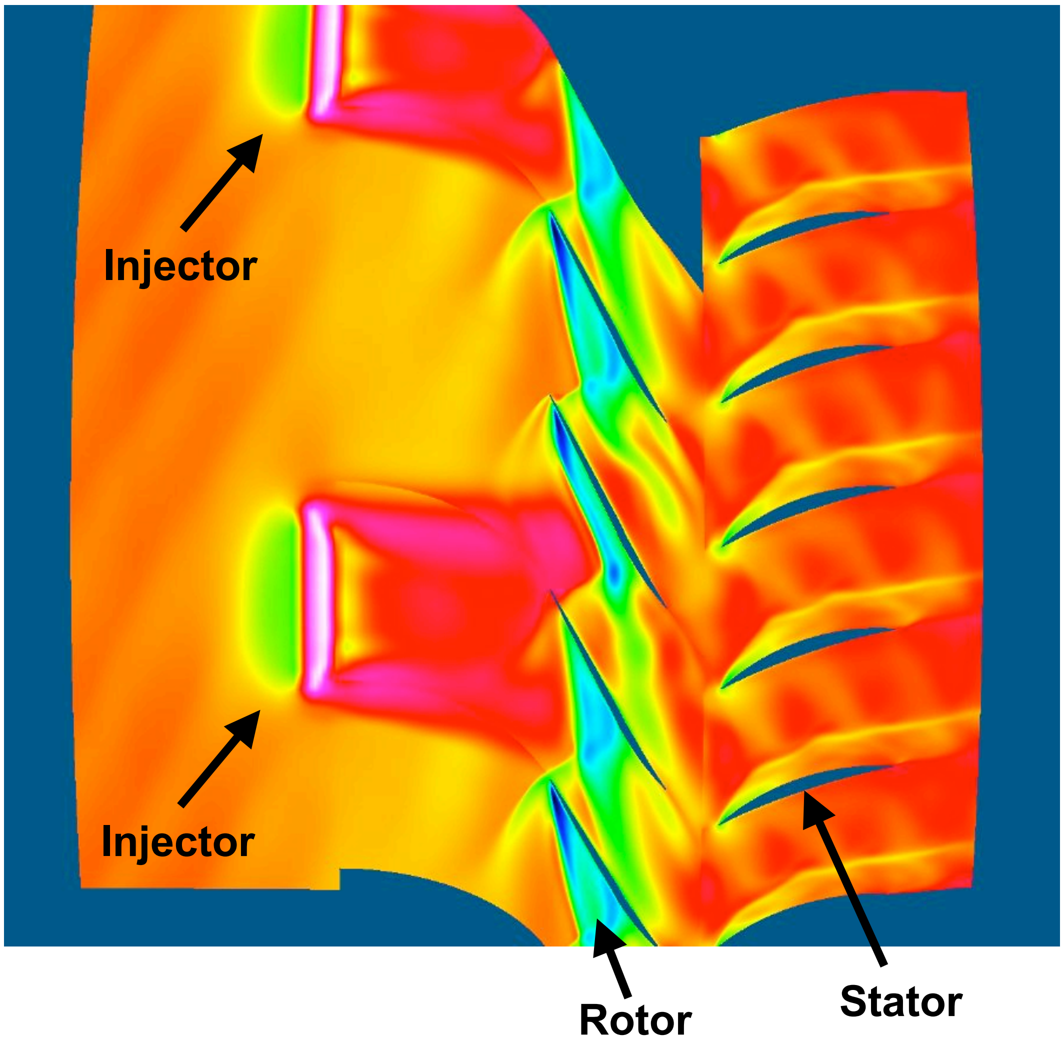
Early experiments were focused on controlled unsteady injection

Rotor Tip Clearance Flow & Stability



Later experiments focused on steady injection and reducing the amount of injected flow required

Rotor Tip Clearance Flow & Stability



Axial velocity contours

Full-annulus MSU Turbo Simulation

12 injectors
36 rotors
46 stators

Summary

Experiments often play an indirect role in advancing turbomachinery technology

Experimental data → CFD validation → Improved design methods

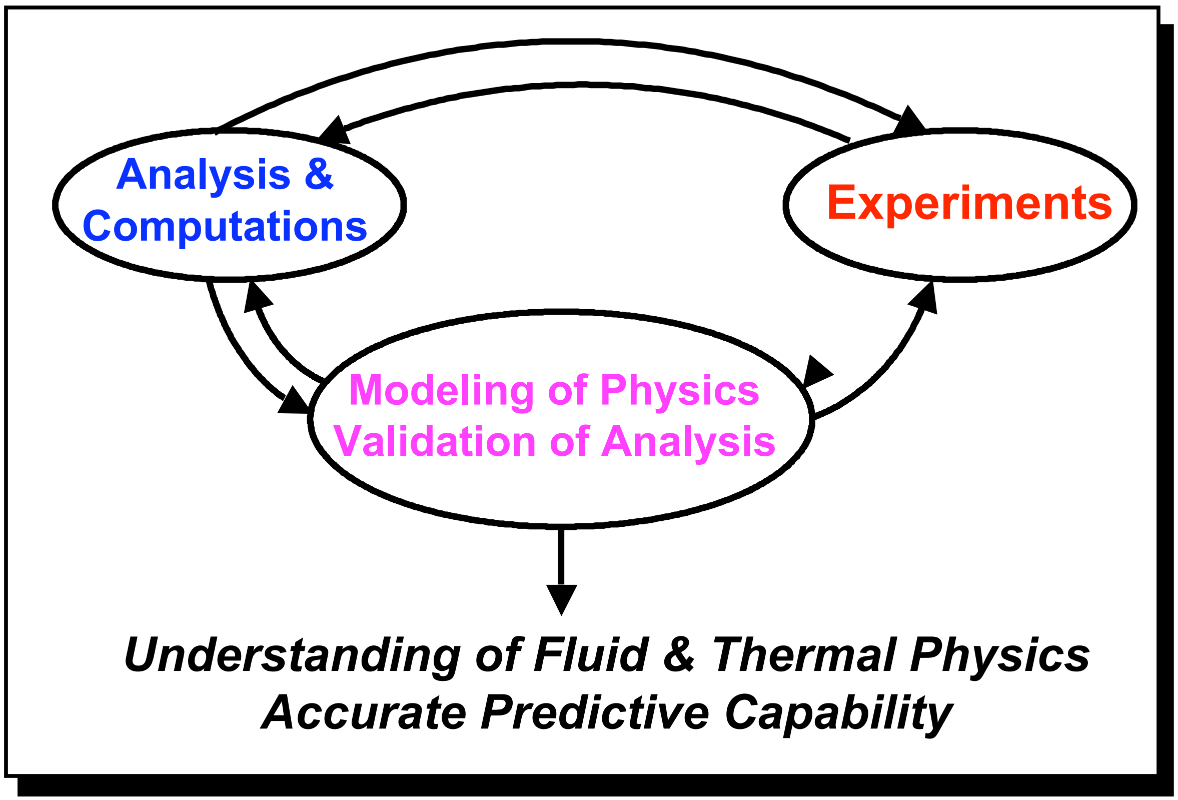
Experiments play a direct role when designed and executed to explore specific fluid mechanic processes within turbomachinery

Experimental data → improved understanding → improved design/ fab methods

The ultimate return on investment is realized when experimental data, numerical analysis, and modeling are used synergistically

The Role of Experiments in Advancing the Design of Gas Turbine Compressors

Summary



"Having a wind tunnel doesn't tell you what to do with it.

Having a computer doesn't tell you what to do with it.

The insight about what to do with a facility is the important thing.

And it is still a human insight."

Wygnanski